

Role of Fly Ash in the Mitigation of Swelling in Lime Stabilised Sulfate-Bearing Soils

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ABSTRACT

Lime stabilisation is widely used to improve both plastic properties and strength of cohesive soils with high clay contents, most commonly in highway construction. The process principally involves the reaction of lime with clay aluminosilicate phases, producing cement-like products. It is a rapid reaction and improvements occur within a few days. The process is now highly mechanised and large areas can be stabilised quickly and at low economic and environmental cost.

However, sulfate phases encountered in some clays can also react with lime resulting in the formation of ettringite. This is an expansive reaction and can produce volume stability problems due to swelling of the stabilised soil. These damaging effects often become visible after completion of the pavement and there are significant costs to rectify the problem.

Fly ash has a well established history of use in suppressing sulfate attack of concrete and grout. Although a different material the chemistry involved in lime-induced ettringite formation in clay is broadly similar and there is growing interest in determining whether fly ash can play the same role in this application.

An extensive study, reported here, was, therefore, initiated to examine the role of fly ash in the lime-stabilisation process and its influences on ettringite-induced swelling. Issues including optimum quantities and timing of intermixing fly ash with clay / lime, as well as the effect of their characteristics, were examined.

INTRODUCTION

Stabilisation with lime can improve the plastic properties and strengthen certain types of clay soil^{1,2}, and is particularly suited to large-scale highway works. It is a simple, fast-acting and cost effective process. It utilises the reaction of lime with the alumino-silicate phases of clays (and water), producing hydrated cementitious products that bond soil particles³⁻⁶. During this, a series of chemical, mineralogical and microstructural changes occur, which lower the plasticity, enhance the load-bearing capacity and enable soil compaction to a higher density.

In practice, quicklime (CaO) is spread over the area to be stabilised, at 2-4% dry weight to a typical depth of 300 mm soil and machine mixed (see Figures 1⁷ and 2). Fly ash⁸ or ground granulated blastfurnace slag (GGBS)⁹ can also be added at various quantities by repeated spreading, rotating and compaction (two-stage mixing operation). The result is a further improvement in the properties of the stabilised soil¹⁰.

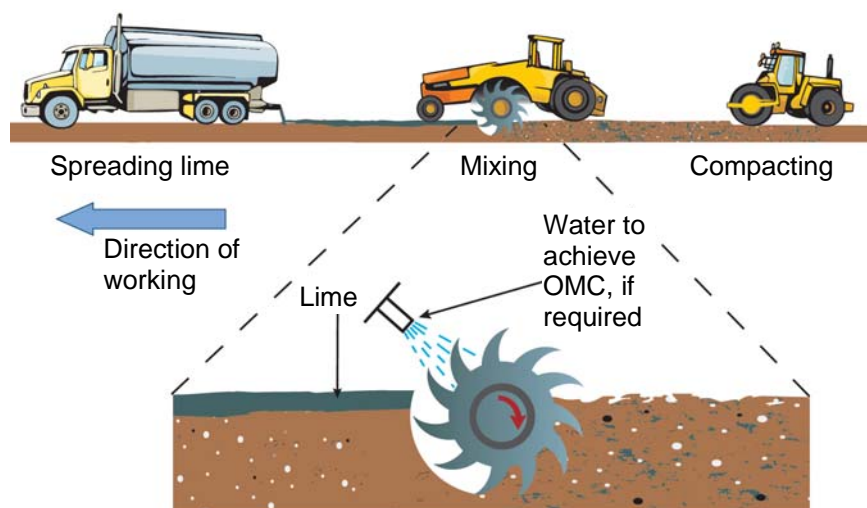


Figure 1. Schematic illustration of the lime stabilisation process⁷



Figure 2. Overview of lime stabilisation technology: mixing hydraulic binder to soft soil and compacting it for a durable hard finish (courtesy of The Concrete Centre, UK)

Although the improvement in soil properties is rapid once mixed with lime, a 'mellowing period' of at least a day⁵ or longer⁶ is typically used prior to compaction. This allows a longer reaction period and improves the benefits achieved. However, during this period, sulfates, present in certain clays, can react with free calcium to form ettringite, which is expansive. If the soil is compacted before the end of this reaction, large volumetric swelling can occur. Unfortunately, there are no simple on-site tests to determine the end of this period and this has resulted in major problems in the past, in both the UK¹¹ and USA¹² (see for example Figure 3).



Figure 3. Typical damage to a highway pavement due to ettringite-induced swelling¹²

As well as sulfates, there is some risk that the aeration of the soil during lime-stabilisation could cause oxidisation of other forms of sulfur-bearing compounds, e.g. sulfides that could also contribute to ettringite formation. For this reason total potential sulfate (TSP) of soil is measured¹³, i.e. sulfur in all valences. If the TSP is >0.25% by mass then it is recommended^{9, 10} that the soil / lime mix is tested for risk of swelling.

Fly ash has many benefits¹⁴⁻¹⁸, including suppressing sulfate attack in concrete and grout and it was the premise of the research, reported here, that it could have the same effect on ettringite-induced swelling in lime stabilised, sulfate-bearing clay soils.

The research was carried out in two phases, firstly to determine whether the addition of fly ash could suppress ettringite formation or its effects and secondly, if different fly ashes behave in the same manner.

PRELIMINARY TESTS

In order to test the premise, initial experiments with a 5:1 quartz sand:montmorillonite artificial soil, spiked with 2% (by mass of solids) sulfate content, as sodium sulfate, were carried out to examine the potential of fly ash to prevent swelling. The test specimens consisted of 40 mm diameter by 40 mm high cylinders of equal solids / water ratio, which were compacted under a specified load for a given time. These were prepared with the addition of 3% hydrated lime and 3, 6, 9 and 12% Type F fly ash (9.8% retention on the 45 μm sieve, 6.0% loss-on-ignition) or 3, 6 and 9% GGBS (with no mellowing).

The test specimens were soaked in water at room temperature and their linear expansion measured daily by micrometer for 28 days as shown in Figure 4.

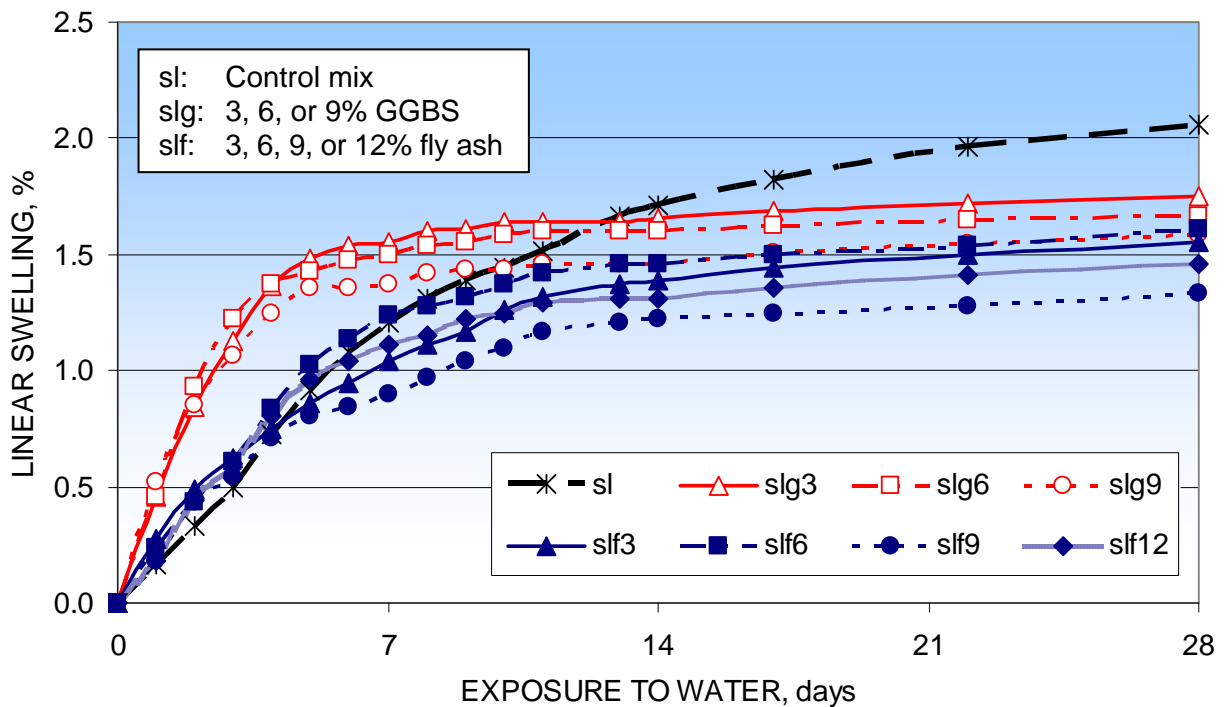


Figure 4. Linear swelling of soil samples containing 3% lime and 2% sulfate

The GGBS mixes swelled quickly, but the expansion of specimens ceased at around 4 to 5 days and was less than the control. With fly ash, the rate of swelling was slower, although this continued for 28 days (i.e. the completion of the test), but its magnitude was lower than that of the GGBS mixes, particularly at 9% fly ash.

At the conclusion of the test, the swelling of the 9% fly ash test mix was >60% lower than the control and given the 12% fly ash mix was less effective, suggests that the role of fly ash was more than chemical in nature¹⁹.

MAIN RESEARCH PROGRAMME

Given the encouraging results from the preliminary tests, a research programme was undertaken to test the performance of a typical range of UK fly ashes. Initially six clay sources were selected with known risk of ettringite-induced swelling, i.e. Gault / Mercia mudstone, Kimmeridge and Lias, Oxford, London and Weald clays (see Figure 5 for geographical / geological distribution). However, it was found that their swelling behaviour was similar and hence only Kimmeridge clay (from Wiltshire, England, UK), whose main properties are given in Table 1, is considered hereafter.

Table 1. Main properties of test clay

SOIL PROPERTY*	
Natural moisture content, %	30.0
Optimum moisture content (OMC), %	24.5
Initial consumption of lime (ICL), %	1.0
Total potential sulfate (TPS)**, %	0.96
Maximum dry density (MDD), Mg/m ³	1.54
Particle density, Mg/m ³	2.70

* BS EN 1924-2²⁰; ** BS 1377-3²¹

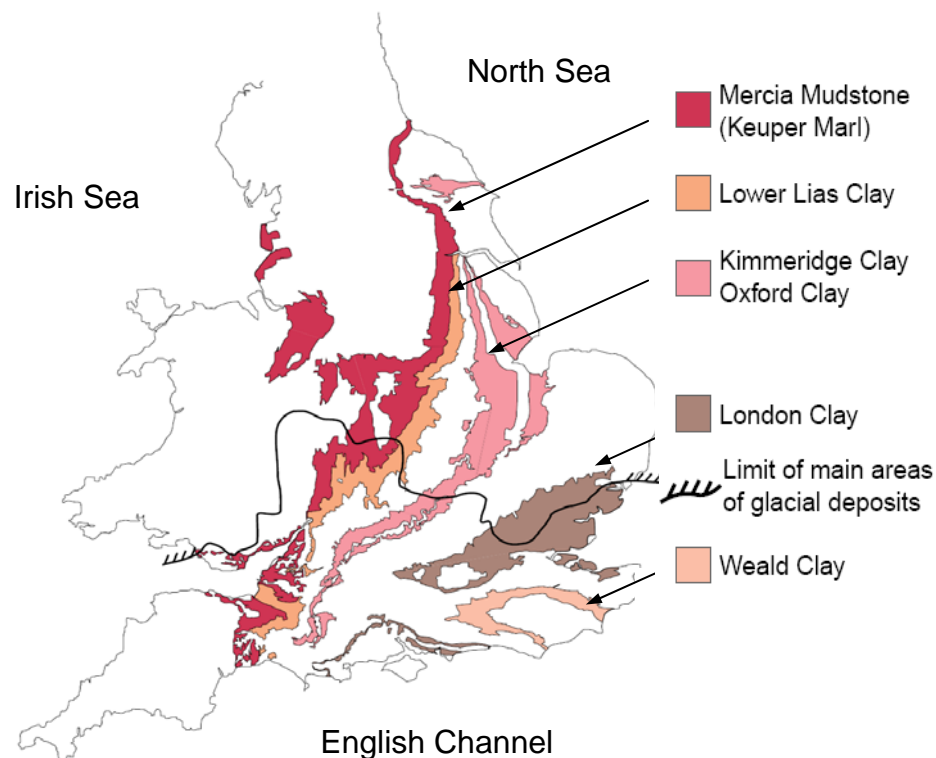


Figure 5. Main sulfate and / or sulfide bearing clay strata in the UK¹⁵

A typically used, commercially available quicklime (CL90) with key particle size characteristics of $d_{10} = 1 \mu\text{m}$, $d_{50} = 44 \mu\text{m}$, $d_{90} = 216 \mu\text{m}$ and conforming to BS EN 459 Part 1²² was used for all tests.

The fly ashes used included a range of fineness and loss-on-ignition values, as well as ashes of different wet storage history, i.e. stockpiled and ponded (all arising from combustion of bituminous coal, i.e. Type F), the physical-chemical properties of which are given in Table 2.

Table 2. Main properties of fly ashes

FLY ASH PROPERTY*	FA1	FA3-1	FA4	FA7
Quality / origin	Type S	Type N	Ponded	Conditioned
Moisture content, %	0.4	0.3	56.0	20.0
45 μm sieve residue, %	10.0	18.6	53.5	46.5
Loss-on-Ignition, %	4.5	3.4	10.7	11.9
Total Potential Sulfate**, %	1.6	0.4	0.6	0.3

* BS EN 450-1²³; ** BS 1377-3²¹

EXPERIMENTAL DETAILS

Test Sample Preparation

The effect of composition (lime and fly ash contents) and the duration of the mellowing period of 0, 1 and 3 days were examined. Batches of materials were prepared, as summarised in Figure 6, by mixing clay, lime and water at optimum moisture content (OMC), which was determined by repeating the Proctor compaction at different water contents and using that giving the highest density.

The material was then hand compacted and kept in airtight polythene bags to mellow for a given period. After mellowing, various quantities of fly ash were added plus any extra water to re-achieve OMC, i.e. the Proctor curve for each particular mix was determined again.

Specimens were then compacted, as shown in Figure 7²⁴, to achieve maximum dry density (MDD), i.e. 50 mm diameter by 100 mm high cylinders for unconfined compressive strength tests²⁵ and 50 mm diameter by 50 mm high cylinders for swelling tests²⁶.

This latter was carried out by the Accelerated Swelling Test Method in BS EN 13286-49²⁶, which prescribes the storage of specimens, wrapped with an elastic textile, in water at 40°C for 7 days (see Figure 8). The volumetric swelling was determined by water displacement, as illustrated in Figure 9.

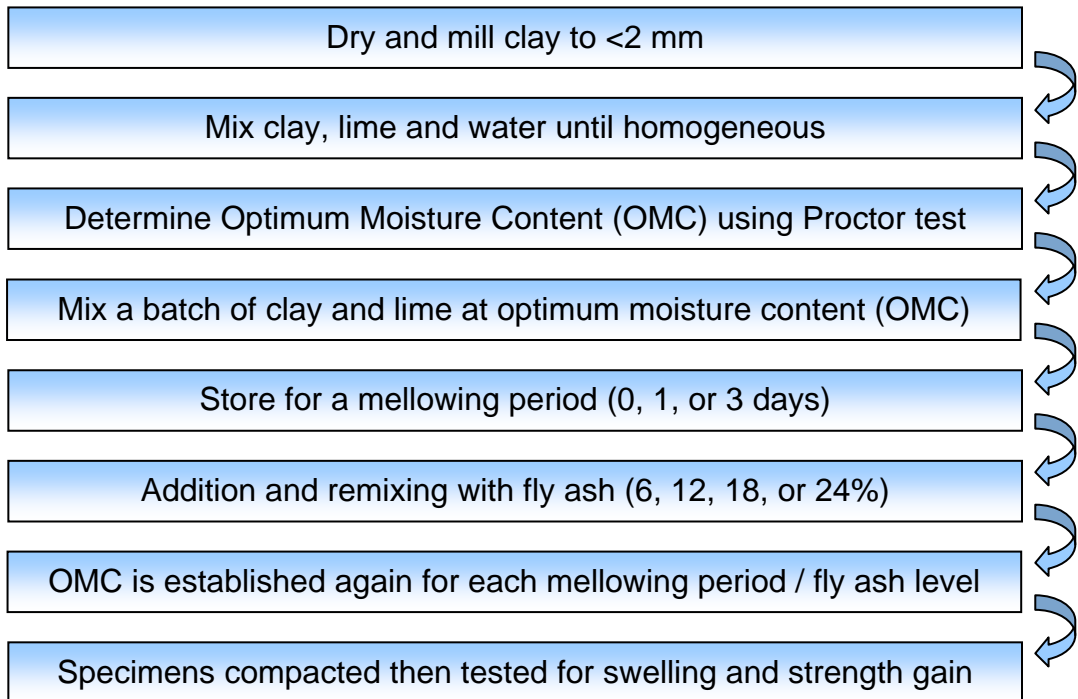


Figure 6. Stages of sample preparation



Figure 7. Mould, piston and displacing collars used for the manufacture of specimens²⁴

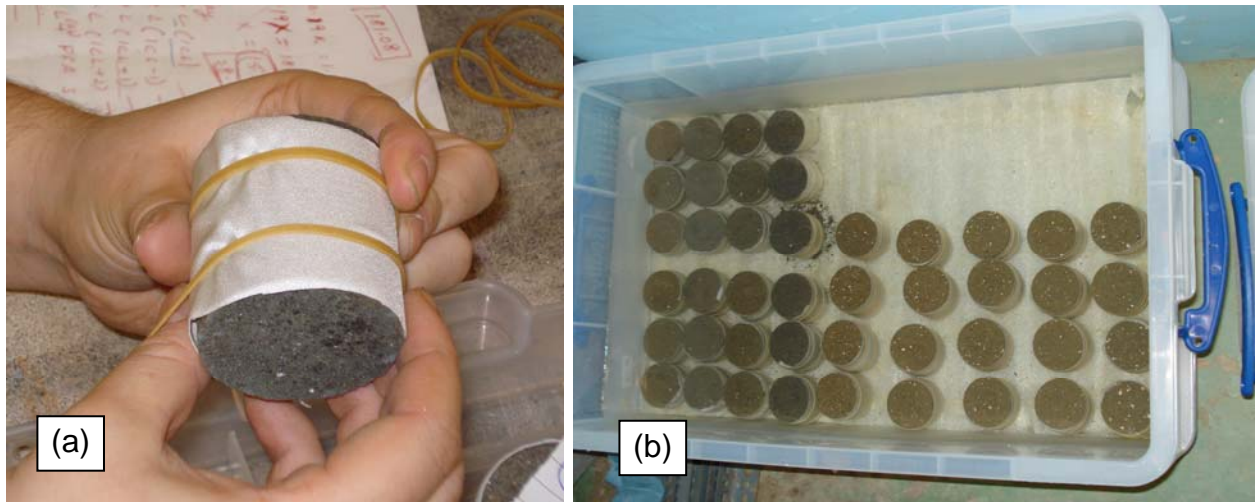


Figure 8. (a) Samples prepared and (b) kept in water at 40°C for 7 days²⁶



Figure 9. Measuring volume change²⁶

Soil : Lime : Fly ash Test Mixes

Table 3 gives the combinations of soil, lime and fly ash used during the main experimental programme, together with the range of mellowing periods. In addition to volumetric swelling, unconfined compressive strength²⁵ and porosity (by mercury intrusion porosimetry, MIP) were measured.

Figure 10 shows a typical outcome after 7 days exposure for control and fly ash test specimens.

Table 3. Clay + lime + fly ash test samples and mellowing periods (MP)

CL90 Lime, %	Fly ash		MP, days	CL90 Lime, %	Fly ash		MP, days
	%	source			%	source	
3	0	-	0	3	6	FA4	1
3	6	FA1	0	3	12	FA4	1
3	12	FA1	0	3	18	FA4	1
3	18	FA1	0	3	24	FA4	1
3	24	FA1	0	3	6	FA7	1
3	0	-	1	3	12	FA7	1
3	6	FA1	1	3	18	FA7	1
3	12	FA1	1	3	24	FA7	1
3	18	FA1	1	4	0	-	1
3	24	FA1	1	4	6	FA1	1
3	6	FA1	3	4	12	FA1	1
3	12	FA1	3	4	18	FA1	1
3	18	FA1	3	4	24	FA1	1
3	24	FA1	3	6	0	-	1
3	6	FA3-1	1	6	6	FA1	1
3	12	FA3-1	1	6	12	FA1	1
3	18	FA3-1	1	6	18	FA1	1
3	24	FA3-1	1	6	24	FA1	1

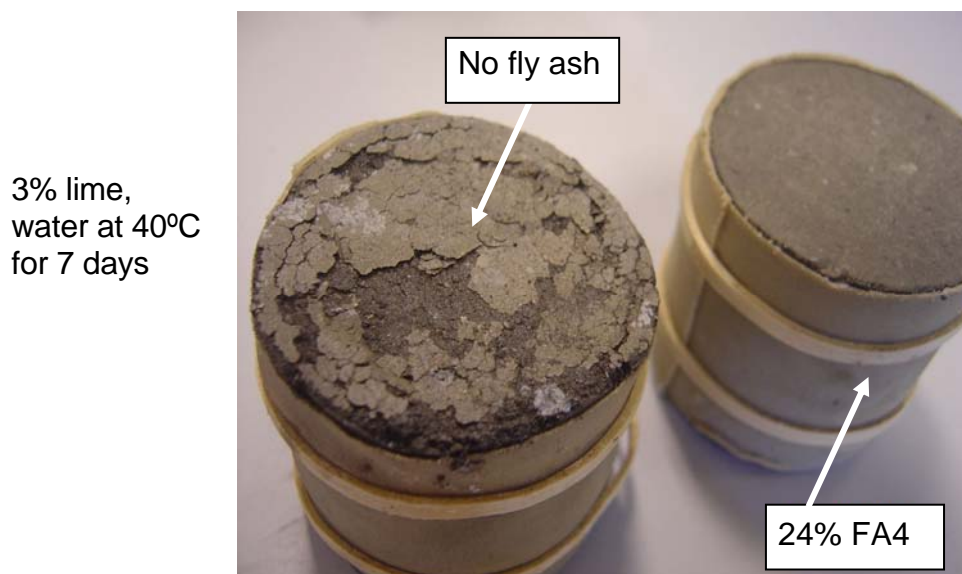


Figure 10. Typical appearance of ettringite-induced swelling and effect of fly ash

INFLUENCE OF CONSTRUCTION VARIABLES ON PERFORMANCE

Effect of Mellowing Period

Figure 11 shows the effect of mellowing period on the volumetric swelling of the test lime stabilised soils.

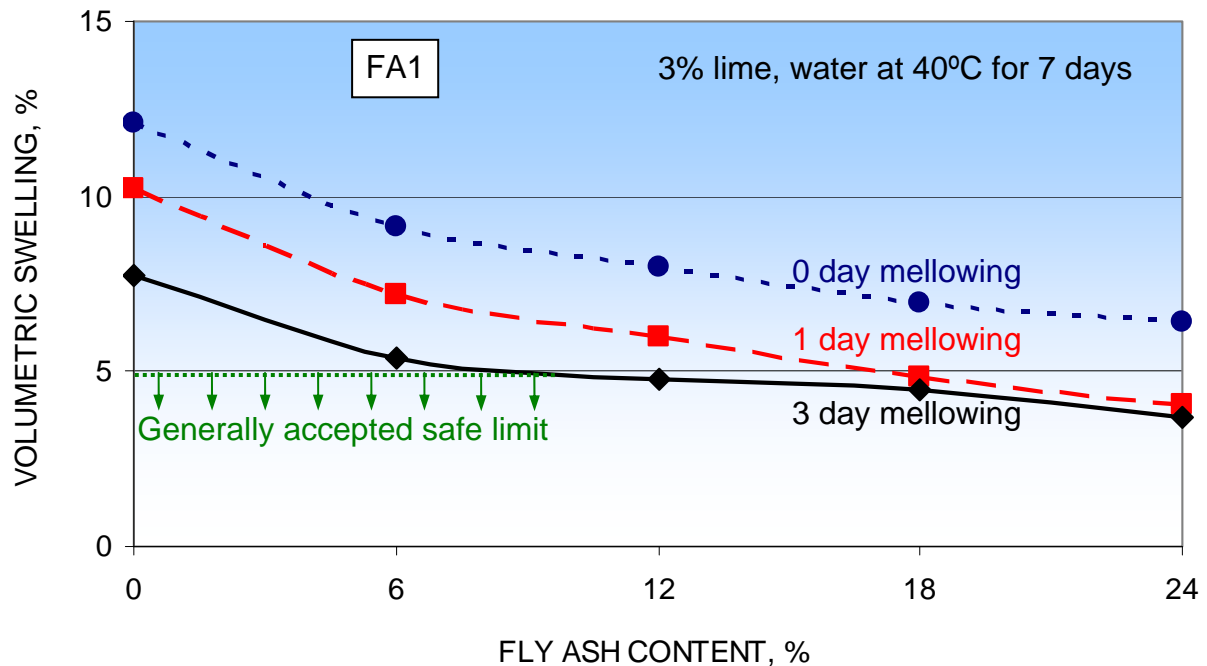
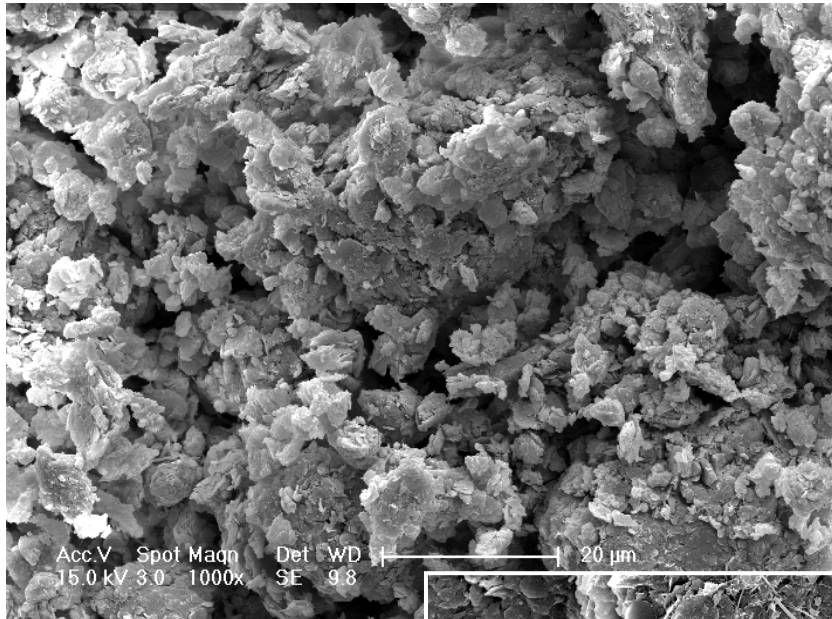


Figure 11. Effect of mellowing period on swelling of clay test mixes

This illustrates that swelling reduced both with increasing fly ash content and mellowing period. The addition of fly ash to the soil simultaneously with lime (0 day mellowing), however, did not impart the required reduction in swelling to achieve the generally accepted upper limit of 5%, even at high levels of fly ash. This was achieved at 1 day mellowing with 18% fly ash and at 3 days with 12%.

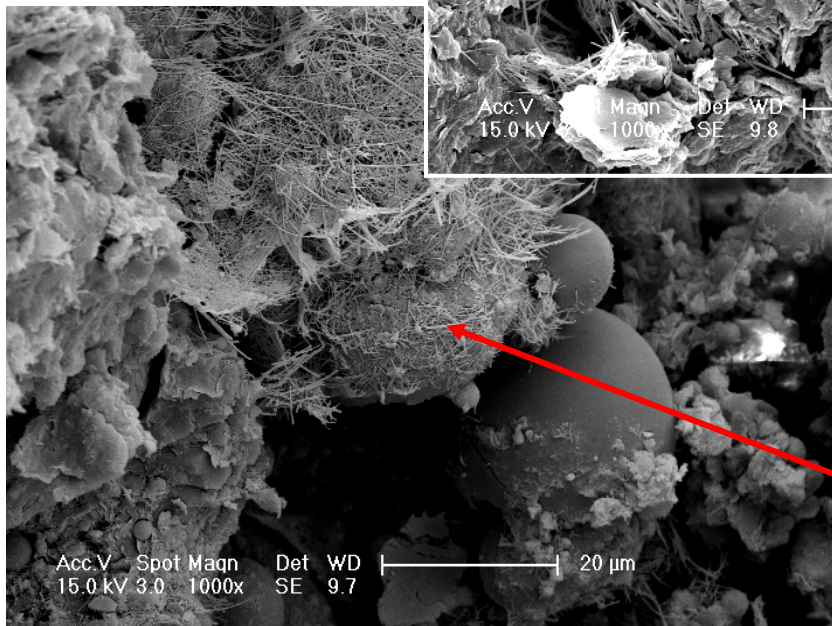
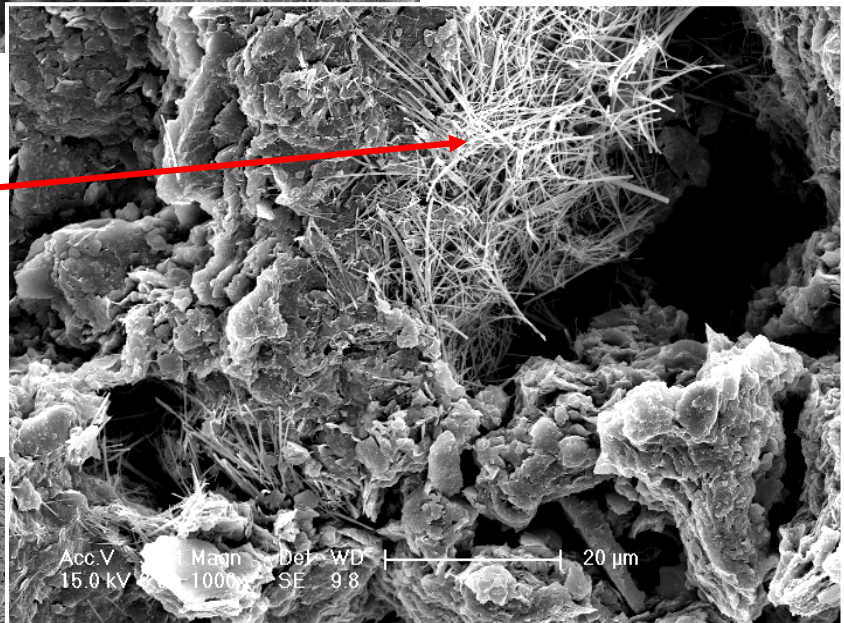
This indicates that the time allowed for ettringite formation prior to compaction is important, as this phase forms at an early stage following mixing with lime. Fly ash may also influence the available quantity of lime for the reaction with clay and possibly affect the flocculation mechanisms during the lime stabilisation process. It is possible that with the elevated temperature of the swelling test, there are additional effects of fly ash that suppress the expansive reaction.

Ettringite formation associated with the process is shown in Figure 12 after storage in water at 40°C for 7 days. This tends to occur near voids, with similar effects noted in both lime and lime / fly ash stabilised soil.



'Raw' clay

Ettringite crystals in
clay stabilised with
4% lime



Ettringite crystals in clay
+ 4% lime + 24% fly ash

Figure 12. SEM images of raw clay and test mixes (40°C water)

Effect of Fly Ash and Lime Contents

Figure 13 shows that swelling reduced progressively with increasing fly ash content. On the other hand, there were only minor differences between the swelling of mixes with different lime contents.

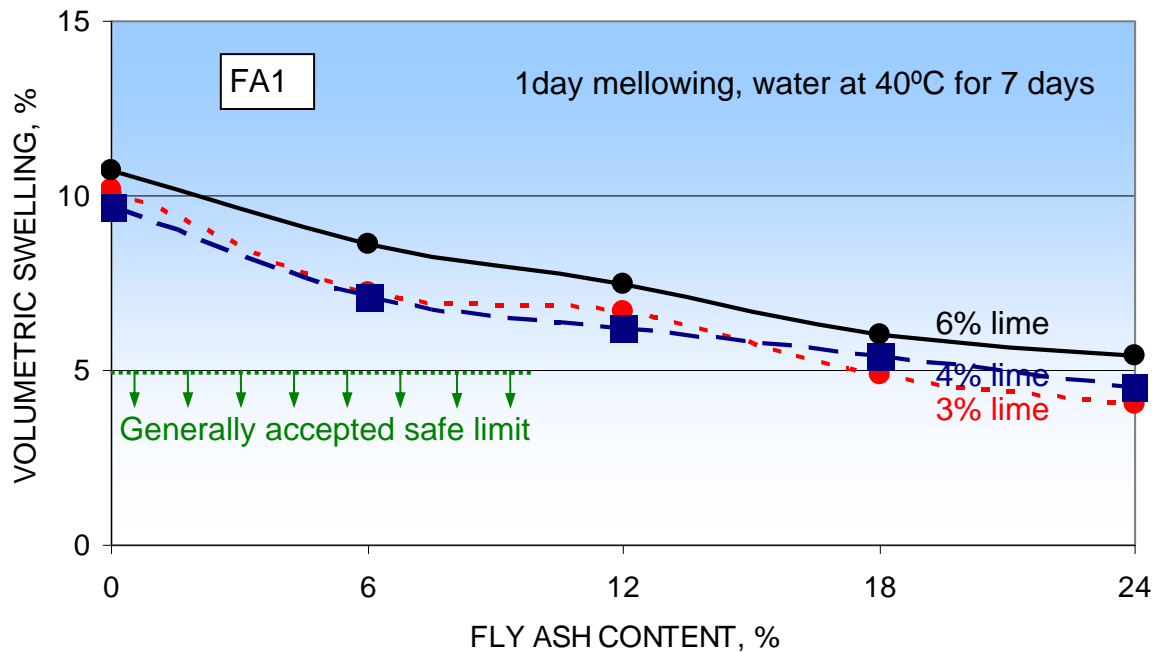


Figure 13. Effect of lime content and fly ash content on swelling

From the stabilisation point of view, a lower lime content would prove to be sufficient and would be preferred to keep costs down. Nonetheless, the results indicate that irrespective of the quantity of lime used in the application, fly ash is effective in mitigating swelling.

The only incentive towards using higher lime contents is to enhance the strength of the stabilised soil, although this is also influenced by fly ash content (see Figure 14). Doubling the lime content from 3% to 6% led to a similar increase in compressive strength of the material.

The effect of ambient temperature and mellowing periods were also examined (see Figure 15). Low temperature had a significant effect on strength development, as expected from experience with fly ash in concrete.

With the mellowing period, contrary to the effect observed for swelling, strength development was not affected if the lime stabilised soil was compacted immediately after mixing. This suggests that the material can tolerate the swelling process without undergoing significant changes in load-bearing capacity.

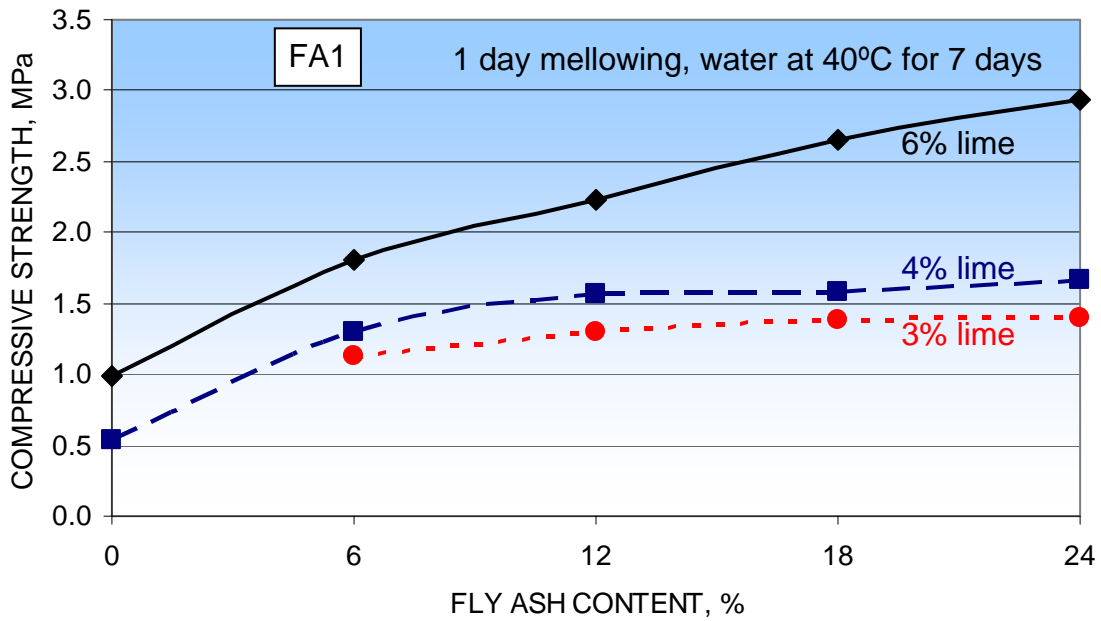


Figure 14. Effect of lime and fly ash content (FA1) on the compressive strength specimens

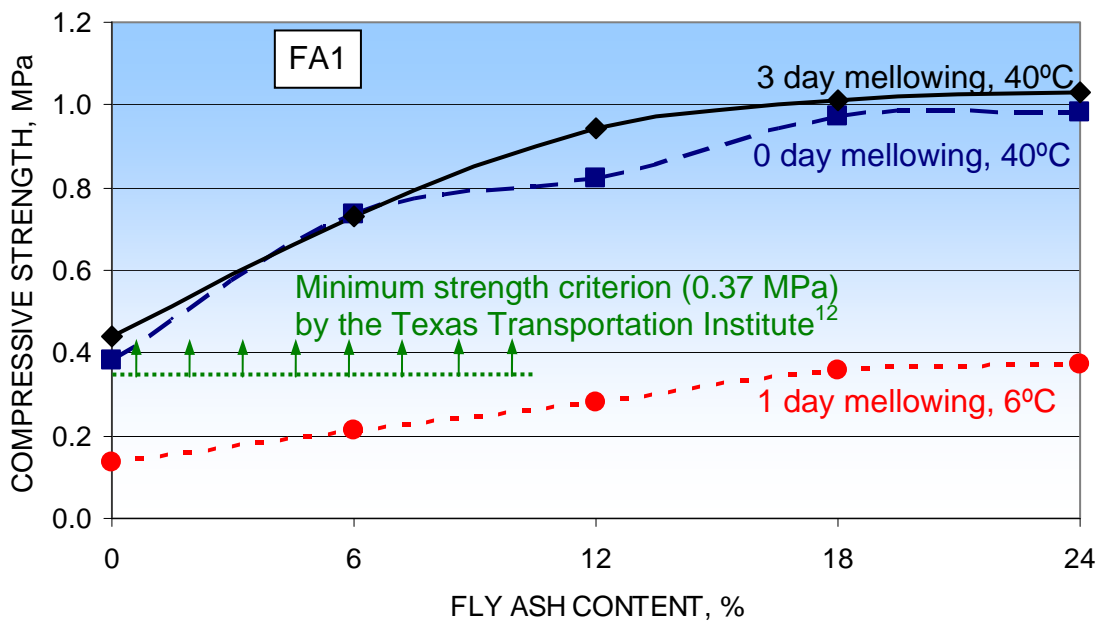


Figure 15. Effect of mellowing period and storage temperature on compressive strength of clay test mixes (3% lime, 7 days)

Effect of Fly Ash Fineness

The range of fly ashes used included those ranging from relatively fine to very coarse (see Table 1). Other properties, such as loss-on-ignition and unburnt carbon and sulfur contents may also play a role but this could not be resolved at this stage of the work.

Based on experience with fly ash in concrete, finer fly ash would be expected to be more reactive. However, Figure 16 shows that coarser fly ash with other comparable properties gave lower swelling than the finer counterpart. This suggests that physical properties of mixes (packing of particles, porosity, migration of moisture, etc.) may also be important. Further investigation is in progress, but initial porosity test results, measured by mercury intrusion porosimetry on freeze-dried samples using liquid nitrogen and moderate (77 mmHg) vacuum, are shown in Figure 17. This indicates that there is increasing porosity associated with increasing fly ash content.

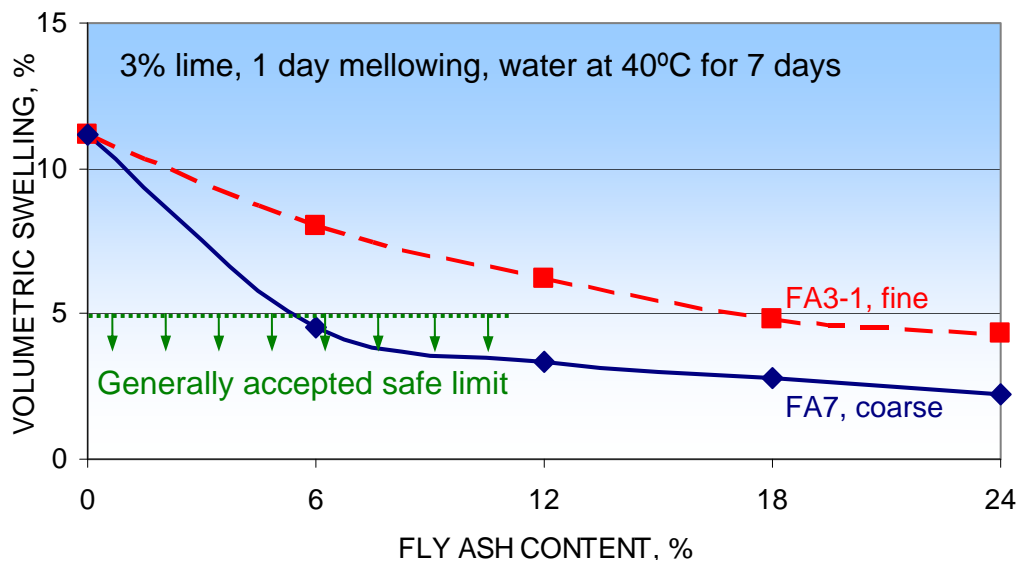


Figure 16. Effect of fineness of similar total potential sulfur content fly ashes on swelling of specimens

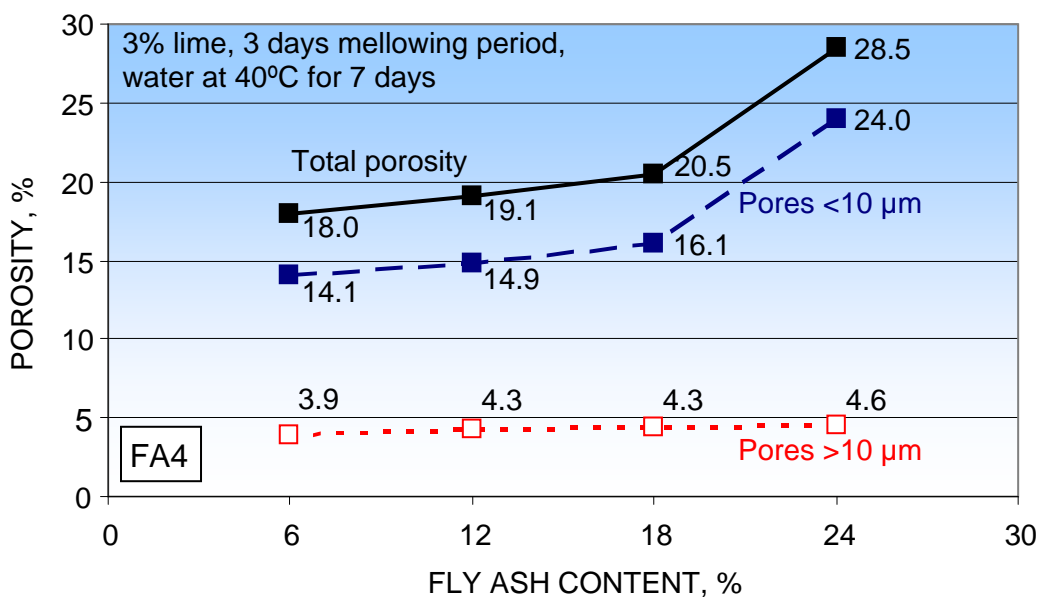


Figure 17. Effect of fly ash content on the porosity (MIP) of stabilised clay mixes

Furthermore, the results also show that there is a correlation between the extra space provided by fly ash addition and the swelling of stabilised soil, see Figure 18, which illustrates the effect of increasing fly ash level. The maximum dry density generally decreases with the use of coarse fly ash and this may also explain the reduced swelling noted with these materials. However, it should be noted that the coarse fly ashes tested in this work also had lower TPS contents but it was unclear whether this also contributed to the reduced swelling observed.

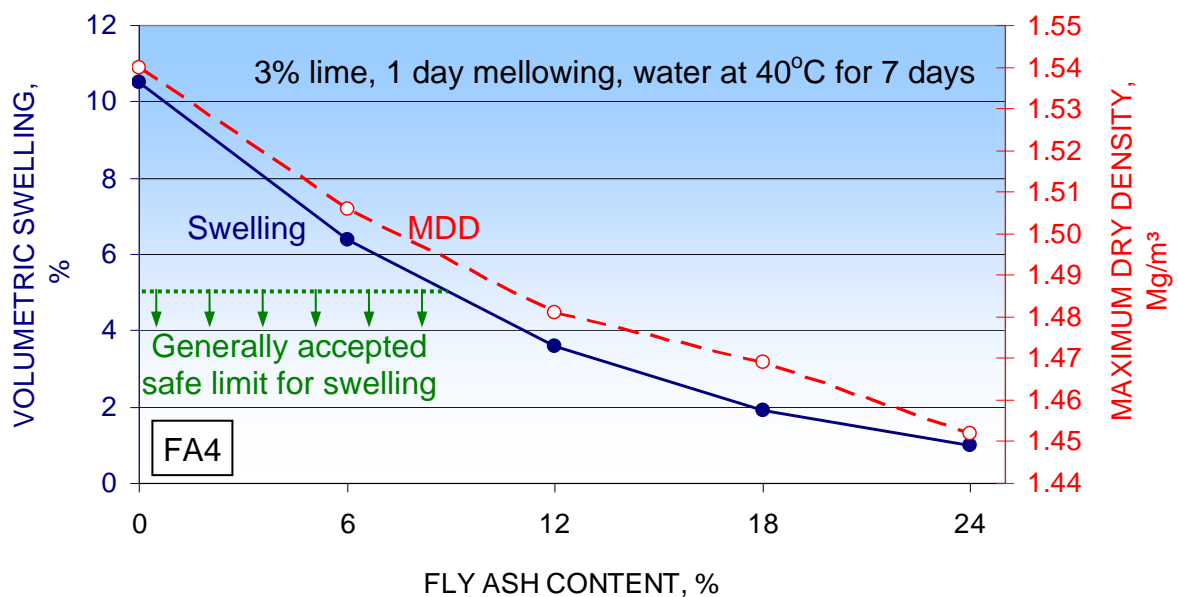


Figure 18. Comparison of trends between max dry density and swelling as a function of fly ash content

CONCLUDING REMARKS

Soil stabilisation is environmental friendly, cost effective and is finding increased use. However, this technology can cause problems with the presence of sulfate in certain soils, leading to ettringite formation and consequential swelling. Fly ash is known to suppress sulfate attack in concrete and grout, and this research was carried out to examine whether it provides similar benefits in this application.

Preliminary work was indeed promising and a full-scale research project has been undertaken. In the course of this, a wide range of clays with known sulfate swelling problems was selected. The results of a typical clay are shown in the current paper in combination with four fly ashes, again representing a wide range of material characteristics in terms of size, composition and wet storage history.

Test soils were produced with a wide range of quicklime (3, 4, and 6%) and fly ash contents (6, 12, 18, and 24%). In addition, a range of mellowing periods (0, 1, and 3 days) prior to remixing with fly ash was applied.

Test soils were then compacted to maximum dry density and stored in accordance with BS EN 13286-49 at 40°C in mains water for 7 days. Cold weather conditions were also simulated using a 6°C exposure. The mitigating effect of the fly ashes, with regard to sulfate-induced swelling, was measured in terms of volumetric change.

Surprisingly, there were similar quantities of ettringite found both in the swollen test reference and fly ash stabilised mixes, which suggests that the mechanism of mitigating sulfate swelling may be unlike that of sulfate attack in concrete.

Unexpectedly, coarser fly ashes with higher loss-on-ignition were more effective than finer ones. This is considered to be due to these mixes achieving a lower maximum dry density, probably due to packing and the results suggest that having more than 20% total porosity provides least swelling. It is, therefore, believed that this 'space' provides 'room' for ettringite growth without affecting overall volume stability. Hence the mechanism is more like the role of air entrainment to mitigate freeze / thaw strain in concrete. It should be noted that this effect has been repeated with other clays.

It was observed that swelling reduced steadily with increasing fly ash and decreasing lime contents. Higher lime and fly ash contents, however, produced higher soil strength.

The mellowing period was found to be important and, in terms of mitigating swelling, the longer this period the better before remixing with fly ash and final compaction. From a practical point of view, 1 day provides a good compromise.

On the basis of these data, albeit accelerated by an elevated temperature, it is suggested that when stabilising a sulfate-bearing clay soil, the most economically and environmentally advantageous process that minimises the risk of swelling, is:

- 3% lime.
- 10 to 15% mass fly ash.
- Allowance of a 1 day mellowing period before remixing with fly ash and final compaction.
- Use of a coarse fly ash, say >30% retained on the 45 µm sieve (although further work is necessary to quantify the effect of sulfate derived from fly ash on this process).

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